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Potential Application of Aerobic Granular Sludge (AGS) Technology in Tofu Industry Wastewater Treatment

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Abstract: The tofu industry produces high protein food but produces wastewater with high organic matter and ammonia which is the result of protein breakdown in soybean seeds during the extraction process. Small and Medium Enterprises (SMEs) sometimes neglect waste treatment due to limited resources. Indonesian regulations stipulate special quality standards for wastewater in the Regulation of the Minister of Environment of the Republic of Indonesia No. 5 of 2014 concerning Wastewater Quality Standards for Soybean Processing Businesses and/or Activities. Indicators of organic matter pollution are characterized by the parameters BOD 150 mg/l, COD 300 mg/l, TSS 200 mg/l, and pH 5-9. Meanwhile, tofu industrial wastewater without special treatment can exceed the quality standard with BOD levels of 5.000-10.000 mg/l and COD levels of 7.000-12,000 mg/l. To overcome this problem apart from using activated sludge, researchers are exploring the use of Aerobic Granular Sludge (AGS) technology. AGS involves aggregate microorganisms in granules to treat wastewater efficiently. This increases treatment efficiency, reduces space requirements, and handles high organic loads effectively. Although aerobic granular technology is promising, research is still ongoing to better understand its characteristics and optimize applications in various industries and environmental conditions. This study aims to explore the potential application of Aerobic Granular Sludge (AGS) technology in treating tofu industrial wastewater with high organic matter content and significant ammonia content so that it meets permitted quality standards.

Keywords: Aerobic granular sludge (AGS); Biological treatment; Organic matter removal; Tofu industry; Wastewater

Introduction

Currently, tofu businesses in Indonesia are mostly still carried out with simple technology, so the level of efficiency in the use of resources (water and raw materials) is still considered low and the level of waste production is also relatively high. Tofu industry activities in Indonesia are dominated by small-scale businesses with limited capital. In terms of location, this business is also very spread throughout Indonesia. The human resources involved generally have a relatively low level of education, and not many have carried out waste processing (Montesdeoca-Calderón et al., 2024). The tofu industry in its processing process produces waste, both solid and liquid waste. Solid waste is produced from the filtering and coagulation process, this waste is mostly sold and processed by craftsmen into tempe gembus, tofu dregs crackers, animal feed, and processed into tofu dregs flour which will be used as the basic ingredient for making dry bread and cakes. While the liquid waste is produced from the process of washing, boiling, pressing and molding tofu, therefore the wastewater produced is very high (Oktorina et al., 2019; Versino et al., 2023).

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Tofu wastewater with characteristics containing high organic matter and quite high ammonia content if directly discharged into water bodies, will clearly reduce the environmental carrying capacity (Sonawane et al., 2022; Fitria et al., 2023). Ammoniacal nitrogen is a major contaminant in municipal and industrial wastewater, causing toxicity to aquatic organisms and eutrophication in water bodies (Chaohui et al., 2022; Zhang et al., 2022; Salbitani & Carfagna, 2021). Sodium ammonia is a chemical compound consisting of sodium and ammonia. Ammonia, which is one of the components of sodium ammonia, can cause harm to human health (Adlimoghaddam et al., 2016). Hazards to the respiratory system: accidental inhalation of ammonia can cause irritation of the nose, throat, and lungs (Wyer et al., 2022; Clausen et al., 2020). Contact with high concentrations of ammonia gas can cause lung damage and even death (A. Wang et al., 2022; Hua & Ou, 2024; Y. Li et al., 2021). To overcome this problem, in addition to using activated sludge, researchers are exploring the use of Aerobic Granular Sludge (AGS) technology (Setianingsih et al., 2024; D. Li et al., 2021; Q. Jiang et al., 2022). Aerobic Granular Sludge (AGS) is a new microbial community that allows the simultaneous removal of carbon, nitrogen, phosphorus, and other pollutants in one system (T. Guo et al., 2024; Hou et al., 2021; X. Guo et al., 2024).

AGS differs from activated sludge in physical, chemical and microbiological properties and offers a simple and cost-effective treatment for removing oxidized and reduced contaminants from wastewater. AGS involves microorganisms in aggregate grains (colonies) to efficiently treat wastewater (Silva, 2023). Based on the description above, this article will review AGS technology in overcoming the problem of tofu industry waste with high organic content and significant ammonia content so that it meets the permitted quality standards.

Method

The method used in writing this article is the literature review method. The author conducted a literature search from various sources such as scientific journals, books, and online articles related to the application of AGS technology in processing tofu industry wastewater. The data obtained were then analyzed and compiled in the form of journal articles. The literature review research methodology is carried out in several stages as follows:

Search Stage

At this stage, the researcher searches for library sources that are relevant to the research topic. Searches can be done through journal databases, books, slides, information from the internet, and others. The keywords used must be relevant to the research topic.

Selection Stage

At this stage, the researcher selects the library sources that have been found. The selected library sources must meet the specified inclusion criteria. The following are the specified inclusion criteria: The article has been published both nationally and internationally indexed; The article was published in the period 2013 to 2023; The article examines AGS (Aerobic Granular Sludge) technology.

Extraction Stage

At this stage, the researcher extracts data from the selected library sources. The extracted data can be theories, findings, and other research materials obtained from library sources.

Analysis Stage

At this stage, the researcher analyzes the extracted data. Analysis can be done using narrative methods or critical methods.

Result and Discussion

The initial stage in this study was to search for library sources. Based on the search results, 14 articles were obtained. From the 14 articles, a selection was carried out according to the inclusion criteria and 9 articles were obtained. After obtaining 9 articles, the next stage was extraction and analysis.

Table 1. Results of Literature Review

Author and Year	Title	Results	Source
(Nancharaiah & Sarvajith, 2022)	Aerobic granular sludge for efficient biotransformation of chalcogen SeIV and TeIV oxyanions: Biological nutrient removal and biogenesis of Se0 and Te0 nanostructures	Ammonium, total nitrogen and phosphorus removal were stabilized at 85%, 80% and 75%, respectively, at 500 µM SeIV and TeIV. 16S rRNA gene sequencing confirmed the known enrichment of SeIV and TeIV reducing bacteria in the granules. qPCR and removal kinetics supported the removal of ammonia via nitritation-denitritation. This work demonstrated the functional capability of AGS to effectively remove	Journal of Hazardous Materials Vol. 422

Author and Year	Title	Results	Source
		toxic SeIV and TeIV oxyanions in addition to performing simultaneous COD, nitrogen and phosphorus removal. Efficient biological nutrient removal in the presence of toxic SeIV and TeIV concentrations, demonstrated the robustness of AGS and its resistance to toxic contaminants.	
(H. Wang et al., 2022)	Enchanced aerobic granular sludge by static magnetic field to treat saline wastewater via simulaneous partial nitrification and denitrification (SPND) process	The results confirmed that SMF increased the average size and readiness of granules, stimulated the secretion of extracellular polymeric substances with high protein content, in turn enhancing aerobic granulation. Although high salt stress inhibited functional microorganisms, SMF maintained better SPND performance with the average COD removal, TN removal and nitrite accumulation ratio finally recovered to 100%, 72.9% and 91.1%, respectively.	Bioresource Technology Vol. 350
(Y. Jiang et al., 2021)	Aerobic granulat sludge system for treating hypersaline pharmaceutical wastewater: Start-up, long-term perfromances and metabolic function.	The results showed that granules could not be formed in 90-day cultivation when directly fed with the target hypersaline pharmaceutical wastewater (RP) due to the suppression of EPS secretion by high concentrations of inhibitory organics, while granules were successfully developed with hypersaline synthetic wastewater (RS) and diluted pharmaceutical wastewater (RD), respectively.	Journal of Hazardous Materials Vol. 412
(Bengtsson et al., 2019)	A comparasion of aerobic granular sludge with conventional and compact biological treatment technologies	The alternative based on AGS is estimated to have a 40-50% smaller footprint and 23% less electricity requirement than conventional activated sludge. Relative to other compact treatment options IFAS and MBR, the AGS process is estimated to consume 35-70% less electricity. This shows the profitable potential for AGS based processes although more experience of AGS operation and performance is available at full scale.	Enviromental Technology Vol. 40, Issues. 21
(Purba et al., 2020)	Various applications of aerobic granular sludge: A review	This article reviews the application of aerobic granular sludge for the removal of nutrients, phenolic compounds and heavy metals from municipal, domestic and industrial wastewater. It discusses the integration of aerobic granular biofloc with membrane technology, microbial fuel cells and microalgae to improve wastewater treatment efficiency.	Enviromental Technology & Innovation Vol. 20
(De Sousa Rollemberg et al., 2018)	Aerobic granular sludge: Cultivation parameters and removal mechanism	The main microbial groups present in AGS and their respective functions are discussed. It is also observed that many parameters taken as current references for LGA cultivation and maintenance can be optimized for energy savings, implementation costs as well as greater resource recovery during wastewater treatment, within the scope of the biorefinery concept.	Bioresource Technology Vol.270 Pages 678-688
(Nancharaiah & Sarvajith, 2019)	Aerobic granular sludge process: a fast growing biological treatment for sustainable wastewater treatment	The results show that other benefits of the AGS process are lower sludge production and resource utilization from excess sludge. The microbial groups present and their unique metabolism contribute to the reduction of sludge production in the AGS process. Extraction of alginate-like exopolymers enhances resource recovery and aids sludge management	Current Opinion in Enviromental Science & Health Vol. 12 Pages 57-65
(Chen et al., 2019)	Characterization of aerobic granular sludge used for the treatment of petroleum wastewater	The results showed that microorganisms in the granules were able to degrade petroleum chemicals consisting of the genera Propioniciclava, Micropruina, Alphaproteobacteria, Flavobacterium, and Sulfuritalea	Bioresource Technology Vol. 271

Strengths of AGS Technology

Aerobic Granular Sludge (AGS) was developed as a better substitute for activated sludge (AS) and overcomes the problem of sludge-water separation in the biological treatment of municipal and industrial wastewater. AGS consists of solid, non-self-moving microbial granules that have a compact microbial structure, high biopolymer content and higher settling velocity. AGS differs from activated sludge in physical, chemical and microbiological properties and offers a compact and cost-effective treatment for the removal of oxidized and reduced contaminants from wastewater. AGS sequencing batch reactors have demonstrated their usefulness in the treatment of slaughterhouse, livestock, rubber, landfill leachate, dairy, brewery, textile and other wastes. AGS is extensively researched for widespread implementation in wastewater treatment plants. Based on the research results, Aerobic Granular Sludge (AGS) technology has the following strengths:

Organic Waste Treatment Capability

AGS is an effective and efficient organic waste treatment technology. AGS can treat organic waste well and produce cleaner wastewater (Liu et al., 2023).

Nutrient Removal Capability

AGS can remove nutrients such as nitrogen and phosphorus from organic waste. This makes AGS very suitable for use in organic waste processing from the food and beverage industry (Pour & Makkawi, 2021).

Energy Saving Capability

AGS requires less energy compared to other organic waste processing technologies. This makes AGS more environmentally friendly and economical (Zueva et al., 2024).

Space Saving Capability

AGS requires less space compared to other organic waste processing technologies. This makes AGS suitable for use in areas with limited land (Amrul et al., 2022).

Cost Reduction Capability

AGS can reduce operational and maintenance costs because it requires less energy and chemicals compared to other organic waste processing technologies (Capodaglio & Olsson, 2019).

From the description above, it can be concluded that AGS is an organic waste processing technology that has strengths in organic waste processing, nutrient removal, energy savings, space savings, and cost reduction. AGS is an effective and efficient technology in processing organic waste and can be used in various industries.

Weaknesses of AGS Technology

Over the past two decades, the AGS process has developed into a mature technology solution for large-scale WWTPs to treat domestic and industrial wastewater. Sustainable wastewater treatment is anticipated using AGS reactors. The main considerations driving the implementation of AGS technology are the significant reduction in land footprint (up to 75%), as well as capital and operating costs (up to 50%) compared to conventional AS processes and other biotechnologies (Tamba et al., 2023). With these economic benefits together with better treatment performance, the AGS process could soon become the standard for sustainable biological wastewater treatment. However, behind some of the advantages of AGS technology, there are several weaknesses of Aerobic Granular Sludge (AGS) technology, including (Guzmán-Fierro et al., 2023).

Requires Long Start-Up Time

AGS requires a longer start-up time compared to other organic wastewater treatment technologies. This is due to the granule formation process which takes quite a long time (Shameem & Sabumon, 2023; Zou et al., 2023).

Requires Intensive Maintenance

AGS requires more intensive maintenance compared to other organic wastewater treatment technologies. This is due to the nature of granules which are susceptible to damage.

Susceptible to Environmental Influences

AGS is susceptible to environmental influences such as changes in temperature, pH, and nutrient concentrations. This can affect the performance of AGS in treating organic waste. From these weaknesses, it can be concluded that AGS has several weaknesses that need to be considered in its use. Nevertheless, AGS remains an effective and efficient organic waste treatment technology in treating organic waste and producing cleaner treated water.

Opportunities for AGS Technology

The conventional AS process is no longer considered sustainable for wastewater treatment due to its large land footprint, higher costs, and complicated process design to achieve biological nutrient removal (nitrogen and phosphorus) (Abdoli et al., 2024; K. Wang et al., 2021). GS has emerged as a new standard for sustainable biological wastewater treatment and to meet stringent waste discharge limits. GS differs from AS in terms of its large particle size, compact microstructure, maintaining slow-growing functional microbes, biopolymer composition, high settling velocity, and lower sludge volume index value. The GS process is more advantageous than the AS process in effectively removing contaminants, tolerance to changes in influent disturbances and lower sludge production. Accumulating evidence suggests that the GS process is suitable for treating sewage and some industrial wastes (Singh et al., 2023; Ksepko et al., 2019).

Currently, the GS process is the most advantageous biological treatment option considering the advanced wastewater treatment coupled with lower land footprint and cost. GS technology could be a better option for new treatment plants and capacity expansion of existing wastewater treatment plants in the coming years, to close the gap. GS technology has been proven to be a suitable option for the treatment of aerobic biological wastewater and various industrial wastes. However, most GS studies have been conducted in laboratory-scale sequencing batch reactors using synthetic wastewater with defined substrates and well-controlled operating conditions, which are not true representatives of real wastewater and prevailing environmental conditions.

Accumulating evidence suggests that GS formation is feasible in medium to high strength industrial wastewater (Hamza et al., 2016). Currently, SBR technology is being considered for STPs in various parts of the world. However, many plants still rely on AS for wastewater treatment. With certain modifications in layout and operation, these SBR AS can be converted into GS systems. This is because GS is superior to AS in removing contaminants and tolerating fluctuations in influent and environmental conditions (Vaksmaa et al., 2023). GS technology also promises to be a promising technology for capacity expansion and new STPs (Aldoseri et al., 2024).

Challenges of AGS Technology

Aerobic granular bioflocs have been predicted to replace conventional activated sludge systems in wastewater treatment plants (Ali et al., 2021). However, the application of aerobic granular sludge in full-scale treatment plants still faces several challenges as follows: It is impossible to convert 100% of activated sludge into aerobic granular biofloc because the process itself removes less dense sludge and only retains sludge with excellent settling properties, resulting in biofloc with low SVI. Therefore, the mechanism to increase the conversion rate of sludge into granules is still a challenge and requires extensive research (Gopinath et al., 2021; Wilén et al., 2018). Most aerobic granulation uses SBR system as the most suitable reactor type. However, the application of SBR in full-scale treatment plants is still a difficult task because most wastewater treatment plants use continuous flow reactors (Matesun et al., 2024; Strubbe et al., 2022). Aerobic granular biofloc may take months to develop. However, the evaluation of granule stability and disintegration process due to unknown factors needs further research.

Conclusion

From the results and discussion above, it can be seen that AGS technology has several strengths and weaknesses. The strengths of AGS are the ability to process organic waste, the ability to remove nutrients, the ability to save energy, the ability to save space, and the ability to reduce costs, while the weaknesses of AGS are that it requires a long start-up time, requires intensive maintenance, and is susceptible to environmental influences. AGS technology is more advantageous than the AS process in removing contaminants effectively, tolerability to changes in environmental influents and lower sludge production. The application of AGS in treatment plants faces several challenges including the difficulty of converting 100% activated sludge into aerobic granular biofloc, most aerobic granulation uses the SBR system as the most suitable type of reactor, and aerobic granular biofloc may take months to develop.

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Conceptualization, Y. A. A. H; methodology, S. S.; validation, M. A. B.; formal analysis, N. I. S.; investigation, Y. A. A. H.; resources, S. S.; data curation, M. A. B.: writing—original draft preparation, N. I. S.; writing—review and editing, Y. A. A. H.: visualization, S. S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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